THE INFLUENCE OF REFLECTION SURFACE SIZE IN CONCERT HALLS

E Green Kahle Acoustics, Brussels, Belgium
O Colella-Gomes Kahle Acoustics, Brussels, Belgium
J Kriz Kahle Acoustics, Brussels, Belgium
V Berrier Kahle Acoustics, Brussels, Belgium
T Wulfrank Kahle Acoustics, Brussels, Belgium
E Kahle Kahle Acoustics, Brussels, Belgium

1 INTRODUCTION

The research presented in this paper was motivated by the question of bass quality in concert halls, namely: how can the architectural and acoustical design of a concert hall be optimised to support and enhance the transmission of sound from bass instruments, such as double bass, cello and timpani, to the audience?

The quality of bass sound in concerts halls is a topic that still remains somewhat elusive – in practice during the design of a concert hall, attention is paid to the seat design, in order to minimise the seat dip effect, as well as to the surface mass of interior sound reflective surfaces to ensure that panel absorption at low frequencies does not become excessive. Over-stage reflectors (canopies) as well as other reflective elements will be sized to ensure that reflections back to the musicians on stage as well as to the audience are sufficiently broadband. The phenomenon that reflections from surfaces of limited dimension have a low-frequency cut-off has been thoroughly investigated by Rindel[1].

In the process of designing concert halls, much emphasis is placed on the optimisation of early reflections. Contemporary 3D ray-tracing tools enable surfaces to be optimised in angle and curvature to provide efficient early reflections to all parts of the audience. Many of the architectural elements in a concert hall which can be optimised in this way – such as balcony fronts, soffits under balconies, specifically angled sections of walls or ceilings – however tend to have dimensions of the order of 1m to 2m. The cut-off frequency for an object of 1m dimension predicted by Rindel's theory is approximately 350Hz (depending also on the distance of the reflector from the source and the angle of incidence). Frequencies below around 500Hz are therefore significantly attenuated. As such, there is a risk that the attenuation of low frequencies due to the seat-dip effect is additionally compounded in halls where the early reflections are highly optimised at mid- and high frequencies but significantly weakened at low frequencies.

This paper describes investigations into the interaction of architectural elements typically found in concert halls and how these can be optimised to enhance bass sound quality. In the next chapters, a brief summary of existing research into bass quality is provided, followed by the results of 2D BEM simulations.

2 PRIOR RESEARCH

Research into the quality of bass in concert halls has occurred in a number of waves. The saga of Philharmonic Hall, New York led Schultz and Watters[2] to discover the seat-dip effect in 1964. Various groups have over the years studied the seat-dip effect in detail, notably university groups in Aachen[3], Salford[4] in the early 2000s and most recently Aalto University[5-7]. This research has been invaluable for concert hall designers, enabling acousticians and architects to optimise seating rakes and seat designs to minimise the strength and subjective impact of the low-frequency attenuation dips.

Beranek[8], Barron[9], and Soulodre and Bradley[10] have carried out wide ranging studies, aiming to find associations between bass quality and objective acoustical parameters. The bass ratio (ratio of RT at low and mid/high frequencies) was an early candidate parameter. Subsequent studies have shown the correlation with subjective bass quality to be weak and that ultimately the bass ratio does not discriminate between halls with good or poor bass quality. Soulodre and Bradley state that "*it is popularly believed that long low-frequency reverberation times are required for a strong sense of bass. The results of the present study do not support this notion*" [10]. In addition, Soulodre and Bradley found that the Early Bass Level (Early Sound Strength up to 50ms in the 125Hz – 500Hz bands) showed the best correlation with the subjective impression of bass sound quality and also state: "*the new finding that the perception of bass is related to the early sound suggests that…long low-frequency RTs may not be the most important factor for achieving strong bass in concert halls. It may be at least equally important to provide early low-frequency energy by using appropriate reflecting surfaces*" [10].

Recent studies by Tahvanainen discuss the "recovery" from the seat-dip effect[6-7]. This research has shown how some halls, even those with a very prominent seat-dip effect in the direct sound and earliest reflections, recover to establish a flatter frequency response. While not demonstrated conclusively by this research, one may posit that the faster a hall recovers from the seat dip, the greater the early bass strength and clarity will be.

For concert hall designers, the question therefore presents itself: how can reflection surfaces be optimised to provide early low-frequency sound energy to the audience, from directions that will suffer less from grazing attenuation, and to optimise the "recovery" from the seat-dip effect?
To the authors' knowledge, no thorough investigation of the low-frequency reflection characteristics of architectural elements typically found in concert halls has taken place.

3 EARLY REFLECTION SURFACES

Before discussing the results of simulations, it is valuable to broadly consider which architectural elements typically found in concert halls could provide early low- frequency reflections? Various studies have led to the conclusion, that reflections must arrive from an elevation of at least 15-30° to be minimally affected by the seat-dip effect[9,11].

The main ceiling is certainly a good candidate. Even if the low frequency reflection arrives outside the 80ms cognitive integration time, there is evidence, both objectively and subjectively that the integration time is longer at lower frequencies[12].

Overhead reflectors or reflector arrays are also possible candidate surfaces, as long as the dimensions of the individual reflectors, or the composite reflection from a reflector array, leads to a sufficiently low cut-off frequency. As mentioned above, Rindel[1] has provided the theoretical background and measurements required to determine reflector sizes and layouts. In addition to triggering the discovery of the seat-dip effect, the saga of Philharmonic Hall, New York also illustrates how an inappropriately designed suspended reflector array can rob a hall of important bass reflections, in particular if the reflector array simultaneously occludes the bass reflection from the main ceiling[2,11]. Whether reflections from smaller suspended reflectors – providing reflections of the harmonics of the bass note and or attack frequencies – combined with later full range reflections from the main ceiling combine to enhance bass quality is still somewhat unclear. Informal listening tests (carried out using binaural computer auralisations) indicate that this might be the case: in this situation the reflector density must be sufficiently low that the bass sound diffracts around the suspended reflectors with sufficiently little attenuation.

Large downwards tilted wall pieces, as found in many vineyard halls such as the Berlin Philharmonie, would also seem to be good candidates to provide full range early reflections to the audience. Even though their size would in most cases be sufficient to generate a broadband reflection, their geometry typically leads again to grazing incidence reflections and seat-dip attenuation.

Finally, balconies and ledges are found in concert hall designs of all typologies. Both the balcony front and connection between the underside of the balcony (soffit) and wall tend to be acoustically optimised when designing concert halls. While these are some of the most common architectural features, they are also amongst the smaller architectural elements in a hall. However, the combined surface – balcony front, soffit and wall – forms an extended surface which could provide useful low frequency early reflections. It is surfaces of this kind that have formed the core of the study presented in this paper.

3.1 Boundary Element Method Studies

The low-frequency reflection characteristics of balconies have been studied in 2D BEM (Boundary Element Method). Five combinations of balcony front, soffit and wall connection were studied – these are described in Table 1 below. The term “downstand” here refers to the combination of a soffit and vertical reflection surface. Typically, this connection will be at 90° (as studied here) but not always. A downstand can be freely suspended in space or form the connection between a balcony and wall. The full side wall and floor have been omitted in these studies, to enable the reflected energy from the other reflection surfaces to be observed more clearly. The point source was located at a height below the reflection surfaces to exclude a horizontal 1st order reflection.

Table 1: Reflector types studied in 2D BEM

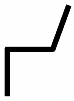
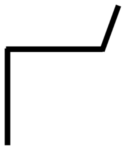
Type	*Description*	*Diagram*	*Type*	*Description*	*Diagram*
A	1m balcony front, angled downwards to return reflected sound towards the source and stalls				
B	1m downstand		D	Combination of 1m balcony front and 1m downstand	
C	2m downstand		E	Combination of 1m balcony front and 2m downstand	

Figure 1 shows the reflected energy level (typically termed “scattered” energy in BEM) for the five reflector types at various frequencies. In the BEM method used, the scattered energy behind the reflector is meaningless – this area has therefore been blanked out in the diagrams.

Prior to discussing the application of these results to concert hall design (see next section), it is worth highlighting a few features of these simulations:

- The reflection from the single angled surface A shows the expected strong reduction in reflection strength with frequency associated with the limited physical size of the object. The simulated reduction in reflection strength compares well with those for a predicted cut-off frequency of approximately 350Hz (calculated according to Rindel[1]).
- As soon as multiple elements are combined, constructive and destructive interference effects become prominent. Taking an imaginary audience plane at the same height as the source, some areas receive reflected energy up to 30dB stronger than others. These “stripes” of constructive and destructive interference are most prominent in the 250Hz simulations with

downstands but are also visible in simulations of reflector types C, D and E at lower frequencies.

- Although according to geometrical acoustics, both the angled balcony front and 90° downstand reflector should return reflected sound energy primarily in the direction of the source, due to low-frequency interference effects, the main reflection lobe(s) can move to very different locations, potentially even with a minimum in the specular reflection direction (back towards the source in this case). This is particularly evident in reflector type C at 250Hz, as well as types D and E at 125Hz and 250Hz.

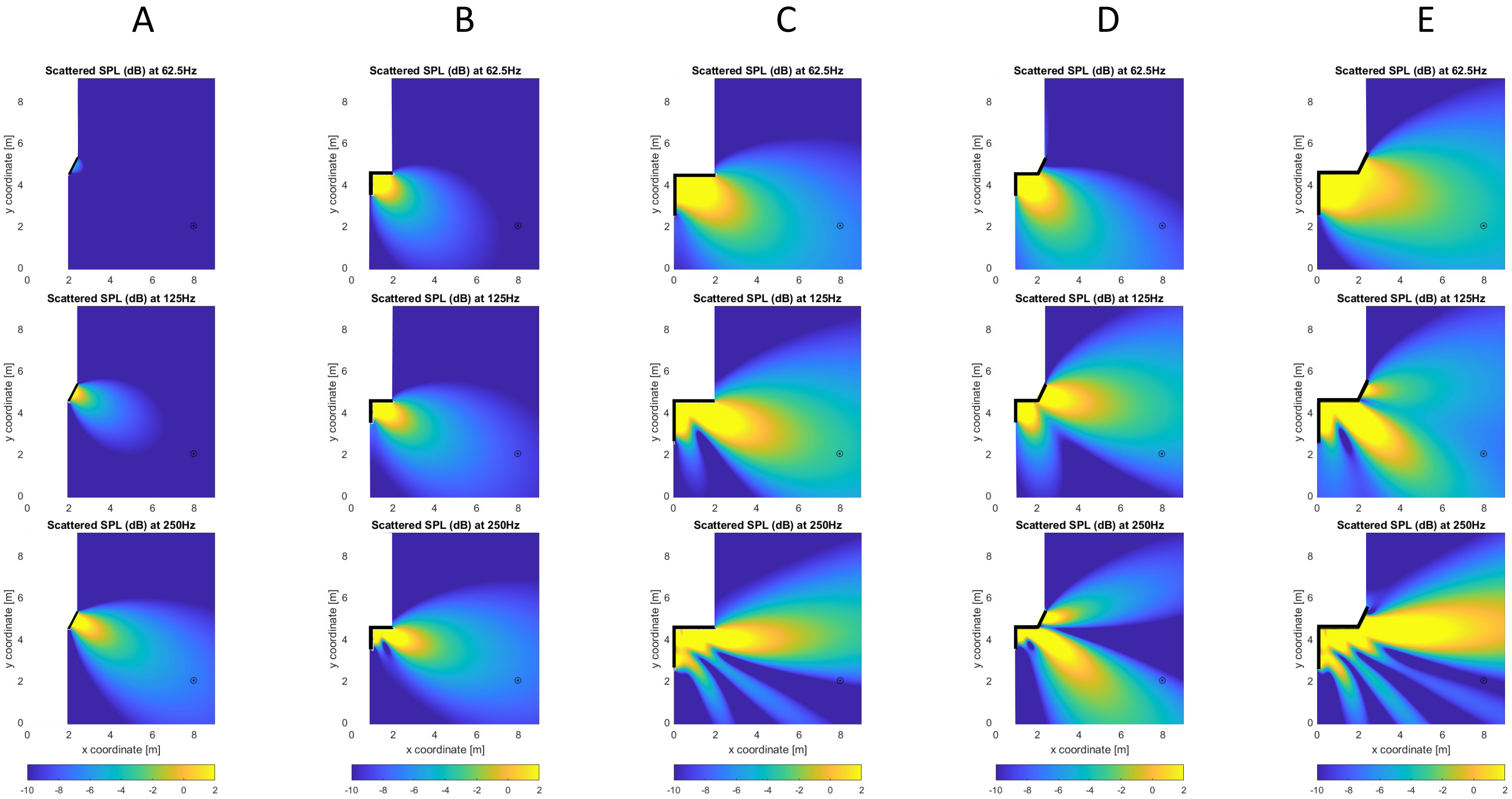


Figure 1: 2D BEM simulated reflected energy levels for the reflector types described in Table 1. The vertical axis represents height above an imaginary floor level, while the horizontal axis represents horizontal distance. No side wall or floor is simulated. The source position is shown as a black dot. The scale of -2dB to -10dB has been set to highlight the shape of the reflection pattern. The true range of values is larger. A large format, high resolution version of the figure is available to download at: https://kahle.be/en/library/articles.html

An alternative way to view this information is to take a horizontal “slice” through a reference plane at a certain height (this could be considered as an imaginary audience or listener plane). Figure 2 shows how the reflected energy levels in such “slices” at the height of the source were “stacked” to produce the diagrams in Figure 3. For these plots 2D BEM simulations were carried out at 85 frequencies corresponding to an equal temperament tuning between A0 (27.5Hz) and A7 (3520Hz). Reflected sound pressure level in the reference plane is illustrated by the colour mapping, while frequency is plotted vertically, and horizontal distance is plotted on the x-axis.

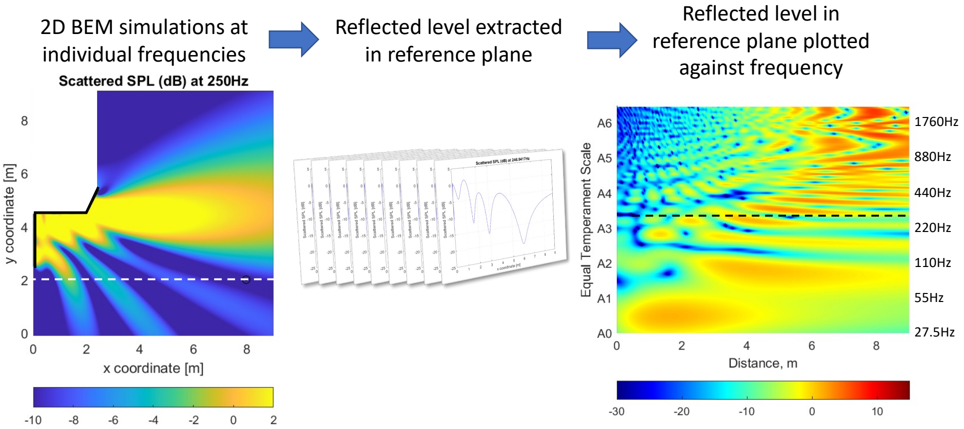


Figure 2: Method to create diagrams shown in Figure 3. Reflected sound levels are extracted from the 2D BEM simulation (here illustrated for 250Hz) at a reference plane (in this example at the height of the source). The reflected levels are then stacked to create the plot on the right where colour represents the sound level in the reference plane for the frequencies of an equal temperament tuning between the musical notes A0 (27.5Hz) and A7 (3520Hz).

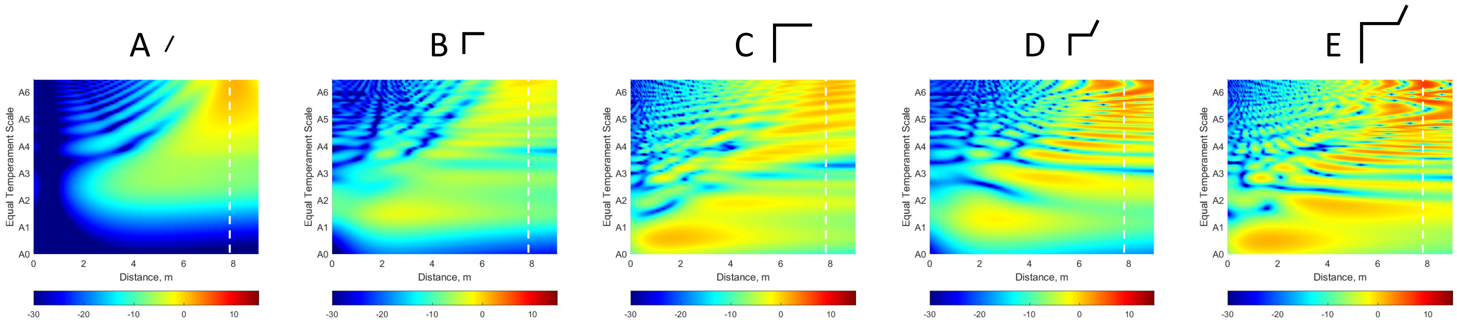


Figure 3: Reflected energy levels across a reference plane at frequencies corresponding to an equal temperament tuning between the musical notes A0 (27.5Hz) and A7 (3520Hz).The source position is as shown in Figure 1 at 7.9m on the horizontal axis, with the reference plane at the same height as the source. A large format, high resolution version of the figure is available to download at: https://kahle.be/en/library/articles.html

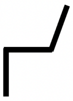
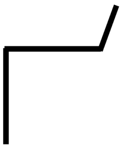
Noteworthy aspects of these plots are the following:

- As one might expect, at higher frequencies, the peak reflection intensity tends to correspond well with the specular reflection direction back towards the source (at 7m horizontal distance);
- With the simple angled surface A, at frequencies below around 200Hz (note A3) the reflected “beam” is much wider than at higher frequencies. In particular at 100Hz and below, the low frequency reflection coverage is spatially significantly wider than at higher frequencies. This is expected to be due to edge diffraction.
- Due to the geometry of the situation under study, the peak reflected strength tends to occur at a lower horizontal distance (“closer to the side wall”) due to the reference plane cutting through the main reflection beam/lobe. This can be seen for instance with reflector type A at 110Hz (note A2). In addition, due to inference effects in the configurations with downstands (B-E), the peak low-frequency energy occurs closer to the wall.

- The peaks in high and low frequency energy can occur in spatially very different places. Taking for example reflector type D, the peak in energy between 50 and 150Hz occurs at a distance of around 2m, while at higher frequencies the peak is at 7m.
- For the same reflector type, the maximum reflected sound pressure level in the specular direction (7m) at high frequencies is consistently stronger than any peak SPL at low frequencies. High frequency peaks can be as strong as 5-10dB whereas low frequency peaks have a level of 2-4dB. Excluding phase effects, this would mean that 2-3 overlapping bass reflections would be required to achieve the same level as a single higher frequency reflection.

Table 2 shows the reflected energy level, integrated (decibel summation) across all positions in the reference plane for the frequency range relevant to the seat-dip effect and bass sound quality (27.5Hz to 293Hz). While the absolute decibel values here are not particularly meaningful, the differences in integrated level between reflector types are meaningful and are significant. This comparison shows that, while the reflected energy distribution across the reference plane (audience) may be extremely inhomogeneous, overall, the larger combined reflection surfaces return more low-frequency sound energy down to the audience. For instance, the combination of a 2m downstand with 1m balcony front (5m total reflector length in 2D) leads to an integrated level 9dB greater than the 1m balcony front alone.

Table 2: Reflected energy level integrated across all positions in the reference plane for frequencies between 27Hz and 293Hz. In general, the larger the total surface size, the greater the total integrated low-frequency reflected level.

Type	*A*	*B*	*C*	*D*	*E*
					
Integrated Level, dB	26	30	34	33	35
Increase, dB	-	+4	+8	+7	+9

4 DISCUSSION: APPLICATION TO CONCERT HALL DESIGN

Research by Soulodre and Bradley[10] and the Aalto University group[6,7] indicates that early bass strength and the provision of early bass reflections is important to the bass quality of a hall and for a sufficient "recovery" from the seat-dip effect. The provision of sufficiently strong, or sufficiently many bass reflections, from non-grazing directions and with a consistent distribution of bass energy both spatially across the audience and over the relevant frequency range would therefore seem to be necessary objectives in concert hall design.

Measurements taken in the Fartein Valen concert hall in Stavanger would tend to support this argument and these objectives[12]. Subjectively, this hall has a strong, clear and warm bass sound, without the indistinctness and "wooliness" that can occur with an overly long bass RT. The unoccupied RT measurements in fact show no bass rise with values between 2.5s and 2.6s in all octave bands from 125Hz to 2kHz (the occupied RT does show a bass rise). The unoccupied early Strength G(0-80ms) at low frequencies is on average only less than 1dB below the 1kHz value, with an early Strength of 0dB at 125Hz equal to the 1kHz value. Notably, some of the most prominent downkicking surfaces in this hall are combinations of downstands (in this case convex curved in plan) and vertically inclined balcony fronts (in this case convex curved), similar to the reflector types D and E studied here. While of course conclusive results cannot be derived from a single example, this nevertheless makes for an interesting case study for further discussion and research.

The BEM simulations show strong “stripes” of constructive and destructive interference, leading to highly inconsistent bass levels within a reference (audience) plane. The positions of the “stripes” depend on the geometric relationship between the source position, reflector position and audience plane. Combining multiple “downkicking” elements in a hall design should therefore move the stripes to different positions in the audience plane, resulting in a homogenisation of the reflected bass level across the bass frequency range and spatially across the audience area. Put another way, multiple bass reflections from different locations and heights are probably highly beneficial to the bass sound quality and potentially necessary to achieving consistent bass levels across all frequencies within the audience areas.

Figure 5: Fartein Valen Concert Hall, Stavanger, Norway. The side balconies are free from the side walls and have “downstands” integrated to provide downkicking early reflections. The balcony form is similar to reflector types D and E studied here in 2D BEM.

Due to the size-dependent low-frequency cut-off, the simulations show that reflected bass sound levels will be significantly lower than mid- and high frequencies for audience areas in the specular reflection coverage area. One could therefore conclude that mid- and high frequency reflections should be attenuated, so that their reflected level more closely matches that of the low frequency reflection. A controlled way to achieve this would be to use convex curvature on the reflector face, to spread the reflection over a greater area and reduce the reflected sound level in the specular reflection direction. Rindel has also provided the theoretical framework for calculating the attenuation due to the convex curvature of reflection surfaces (and indeed the amplification or attenuation of concave elements)[1]. Examples where this has been put into practice are the concert halls in Stavanger and Bordeaux[12,13].

Furthermore, it can be considered an acoustical advantage that the peaks in the low-frequency reflection do not occur in the same location as the mid- and high frequency peaks and that the low-frequency reflection peaks are more spatially extended. In halls with multiple downkicking reflection elements, audience areas would therefore potentially receive a greater number of bass reflections than mid- and high frequency reflections. In this case, the cumulative level from multiple bass reflections should also help to match the level of the higher frequency reflection(s).

In many ways, hall designs with multiple balconies such as Fartein Valen in Stavanger and some historic halls will somewhat automatically integrate low-frequency downkicking reflection surfaces at multiple heights. Their integration into other forms of hall design is certainly possible, for example through the use of suspended lateral reflectors such as in the Philharmonie de Paris. In general, the larger the surface, the stronger and more consistent the bass reflection coverage will be, but it can also be concluded that surfaces with dimensions of the order 1m can certainly be used in concert hall design to orientate early bass energy towards audience areas and, in combination with other larger surfaces, generate sufficiently high early bass sound levels.

In discussing these simulations, and translating the results to concert hall designs, it is important to also consider that the BEM simulations use a single point source. Most airborne room acoustics measurements also use a point source (or at least an approximation thereof). In most situations on real stages the source would however be spatially extended, either due to the interaction between the instrument with the stage floor or due to multiple instruments performing together. With an enlarged source the large variations generated by interference effects will be smoothed out.

Furthermore, the combined radiation of the instrument and stage is also believed to be an important contributing factor to overall bass quality[14]. Similarly, the haptic response of the audience floor - either by direct vibration transmission from the stage or by airborne excitement – is believed to provide a significant contribution to the overall subjective bass response[14]. Psychoacoustic effects such as the auditory compensation for the “missing fundamental” will certainly also play a part. None of these phenomena are currently captured by standard room acoustics measurements or by laboratory-based listening tests, but together with the airborne bass sound transmission will combine to form the overall impression of bass sound in a real hall.

5 CONCLUSIONS

Simulations of reflected bass sound energy from architectural structures typically found in concert halls – such as suspended reflectors, balcony fronts, downstands and soffits – have been carried out using 2D BEM. These simulations show that, due to the limited size and corresponding diffraction effects, the reflected bass sound in the theoretical specular reflection coverage area is significantly weaker than the mid- and high frequencies and that the level is highly inhomogeneous within the audience plane. The bass reflection coverage is however extended spatially, spreading to areas substantially outside the theoretical specular reflection area. The result is that audience areas outside the mid- and high frequency reflection coverage area potentially do receive a relatively strong bass reflection, helping to offset the low-frequency loss in reflection strength compared to higher frequencies.

To compensate for the seat-dip effect and provide sufficient early bass energy with a homogenous spatial coverage and even frequency response, multiple bass reflection surfaces would be required with a non-grazing relationship to the audience. While there are many aspects of bass sound quality that require further research, in practice, a combination of multiple balcony levels and/or multiple overhead reflectors with different spatial relationships to the audience would seem to be required to achieve a strong early bass sound and good overall bass sound quality.

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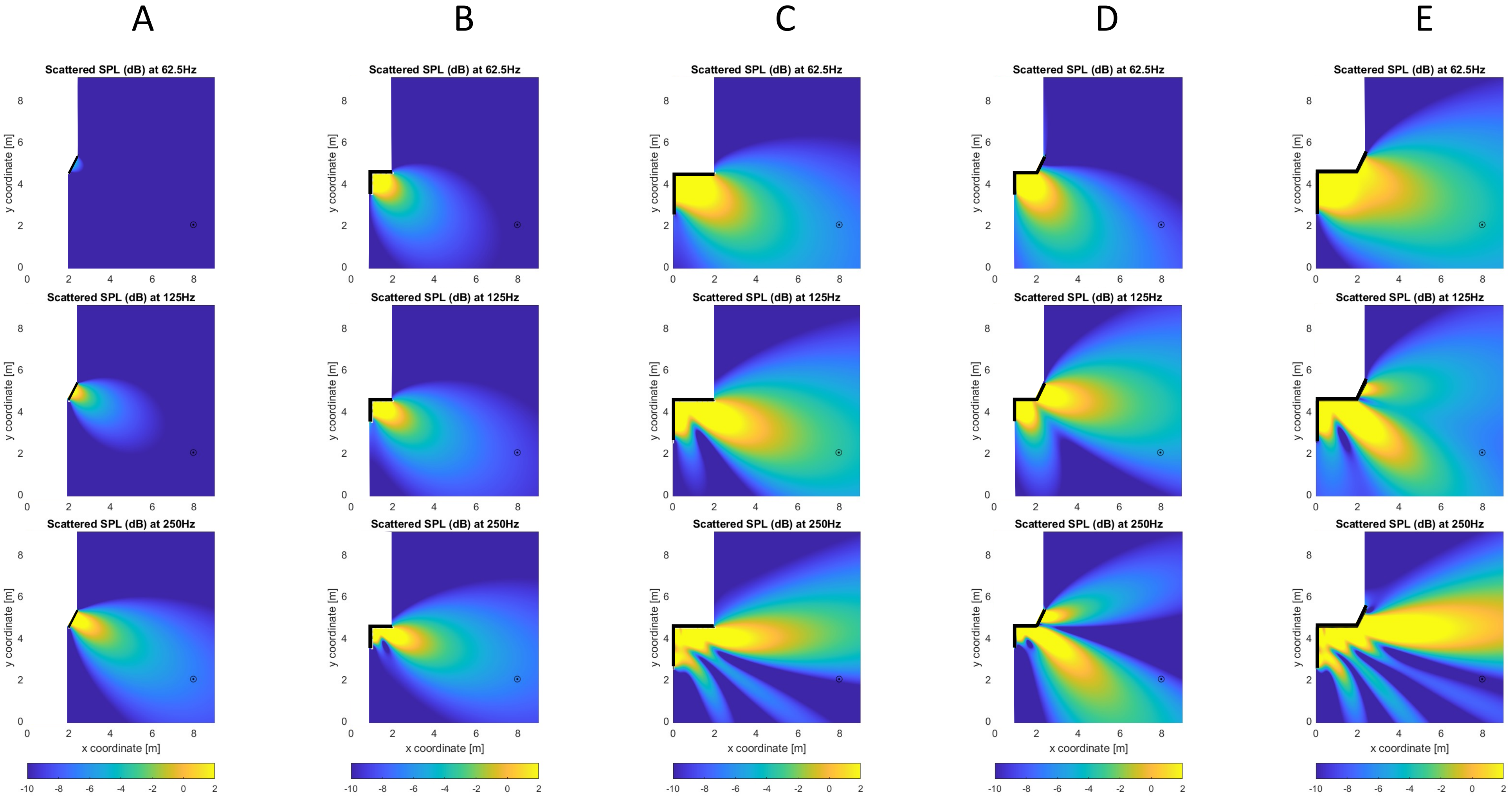
A
B
C
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Scattered SPL (dB) at 62.5Hz
Scattered SPL (dB) at 125Hz
Scattered SPL (dB) at 250Hz
y coordinate [m]
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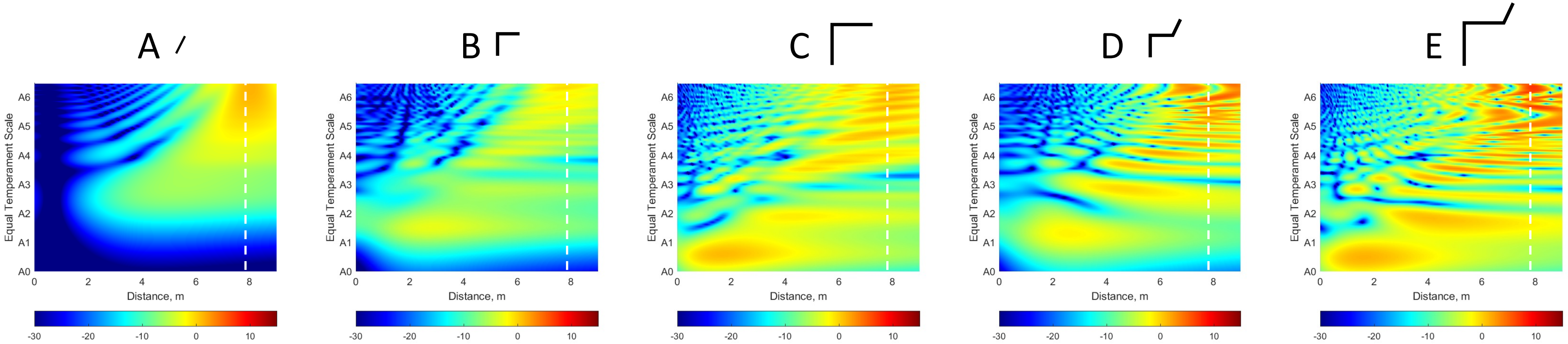
A
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